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# Integrated AHP–TOPSIS–VIKOR Analysis for Selecting Bio-Based Chemical Feedstocks

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## Abstract

The increasing demand for sustainable chemical production has heightened the need for identifying optimal bio-based chemical feedstocks that can substitute in place of fossil-derived resources. Feedstock selection is inherently complex as it requires consideration of multiple and often conflicting criteria around their technical performance, economics, environmental sustainability and market readiness. This study proposes an integrated multi-criteria decision-making (MCDM) framework consisting of the Analytic Hierarchy Process (AHP) for weightings, combined with two ranking algorithms, namely, Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) and VIKOR, to allow multi-criteria assessment and ranking of bio-based chemical feedstock alternatives. Weighting of relative importance of specific criteria (such as availability, cost, conversion efficiency, environmental impact, and market demand) for ranking feedstock alternatives was done through AHP and, subsequently, two ranking methods (TOPSIS and VIKOR) are used to rank algae biomass, lignocellulosic biomass, agricultural residues and vegetable oils alternatives based on their distance to the ideal solution and compromise ranking, respectively.

Both TOPSIS and VIKOR yield consistently similar ranks with algae biomass as the most attractive feedstock owing to its greater conversion efficiency and environmental performance overall. Sensitivity analysis undertaken (20% increase and decrease of weights), confirms the robustness and relative stabilities of the overall ranks of results of the ranking of feedstocks derived through the proposed model. Overall, the integrated AHP–TOPSIS–VIKOR framework will serve as a transparent and reliable decision-support tool for researchers, regulators and industrial stakeholders in their efforts towards fast-tracking the uptake of bio-based chemical feedstocks and in particular, in terms of best feedstock selection.

**Keywords:** AHP; TOPSIS; VIKOR; Bio-Based; Chemical Feedstocks

## 1. Introduction

In response to the increased demand for cleaner and more sustainable chemical production, a drive for sustainable bio-based chemical feedstocks that allow reduced tirp to fossil-based feedstocks has accelerated. Bio-based substrates have great environmental promise (including algae and biomass lignocellulosic, vegetable oils and chemical feedstocks like agricultural and food waste); however, their actual implementation as viable sustainable feedstocks for existing chemical systems is limited by significant uncertainty and variance in availability, conversion efficiency, economic attractiveness, environmental performance and maturity of market. A higher the level of variability and complexity in selection of an optimal feedstock makes a corresponding higher demand for a decision problem approach that considers conflicting objectives and multiple uncertainties. The field of bio-based feedstock selection is new, and relatively few studies exist. Available literature focuses its attention on one or other of the objectives; multiple criteria studies have only recently started to appear, and largely make use of life cycle analysis (LCA), retrospective judgements or economic isolated aspects that do not strongly correlate to an MCDM approach. In this work the authors attempt to fill both

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research gaps by contributing an integrated AHP–TOPSIS–VIKOR methodology to allow the objective selection of bio-based chemical feedstocks while taking both economic and environmental relative merits into consideration simultaneously.

Exploiting the strengths of three AHP–TOPSIS and VIKOR for integrating expert opinions "the consensus ranking", using integrated criteria from (economic-environmental) pairwise comparison for calculation of weights. Using comparison to a paradoxically alternative "anti-optimum solutions" makes the results less susceptible to bias shifting in preference for "less desirable" options. The visualisation obtained from these two algorithms, makes it even more convincing that rankings are valid "robustness analysis". Finally, it also allows one and other cross-comparison to help ensure selections are doubly 'consistent', which the authors are actually the first to be conscious are still absent from a lot of recommendations now available in the literature. The case study then discusses ranking of traditional feedstock and bio-sources based on sustainability. Analysis of selected feedstocks; (±20 percent sensitivity graphically), which helps to get greater clarity on the overall suggested feedstock family weight.

## 2. Literature Review

A number of multi-criteria decision-making (MCDM) methods have been used to solve many different types of sustainability issues that involve both quantitative and qualitative data and also conflicting criteria. In the case of bio-based chemical and energy systems, MCDM provides a structure for evaluating both technical and economic performance, as well as environmental and market performance at the same time [1-3]. A number of researchers have identified three of the most commonly used MCDM methods analytic hierarchy process (AHP), technique for order preference by similarity to ideal solution (TOPSIS), and VIKOR because they are transparent and easily implemented and provide a high degree of decision interpretability [1-3]. There have been a number of recent publications that have focused on selecting a feedstock using MCDM methods. For example, Samanlıoglu [4] developed a fuzzy AHP-TOPSIS approach to rank plant-based biodiesel feedstocks based on yield, cost and conversion efficiency, which had an influence on feedstock priority. Velasquez and Hester [5] demonstrated the applicability of MCDM methods in assessing sustainability and stated that feedstock selection required a holistic evaluation of all criteria, rather than a single criterion. Other researchers who evaluated lignocellulosic biomass and agricultural residues using AHP, along with TOPSIS and COPRAS to select optimal feedstocks for both bio-energy and biochemical production [6,7].

More recent publications have extended the application of MCDM to assess environmental life cycle indicators and policy driven sustainability objectives. Liu et al. [8] showed how to integrate LCA indicators into a TOPSIS methodology to evaluate various biomass utilization pathways, and demonstrated how environmental indicators changed the ranking of feedstocks relative to those ranked solely based on cost. Likewise, hybrid AHP-VIKOR methodologies were demonstrated to be useful for renewable energy planning and optimizing biomass supply chains through finding a compromise solution that balances the group utility and the individual regret [9,10]. Although there has been significant advancement made in applying MCDM, the existing body of literature has noted significant limitations. The majority of published studies use one ranking methodology and therefore the resulting rankings are dependent upon the specific assumptions associated with each methodology [11]. Furthermore, while some studies assign arbitrary or equal weight to criteria, many do not verify the consistency of the weights assigned, thereby limiting the decision reliability [12]. Sensitivity and robustness analyses are rarely conducted or if conducted are limited to a few qualitative statements and although ranking stability is essential for informing decisions by government agencies and private industry, the lack of such analysis severely limits the value of the study results [13]. Recent review articles highlight the need for developing integrated MCDM frameworks that incorporate multiple ranking methodologies and sensitivity analysis to increase the robustness of the resulting rankings [14,15]. The development of such integrated frameworks would be particularly beneficial for selecting sustainable bio-based chemical feedstocks since the uncertainty in the future availability of resources, the maturity of technologies, and the potential environmental impacts may significantly affect the long-term sustainability of selected feedstocks. To fill this gap, the current study advances the state-of-the-art by combining AHP for consistent weighting of criteria with TOPSIS and VIKOR for cross-validation of feedstock rankings and supporting the resulting rankings with rigorous weight-based sensitivity analysis. As such, the study will directly address the methodological fragmentation found in previous studies and develop a robust and reproducible decision-support framework for selecting sustainable bio-based chemical feedstocks.

## 3. Methodology

Construction of the decision matrix and the establishment of the selection criteria for the suitability assessment of the bio-based chemical feedstocks involve multiple criteria which may be competing (techno-economic feasibility, environmental sustainability, etc.) - therefore it is necessary to apply a multi-criteria decision-making method (MCDM).

The initial step of MCDM is the development of the decision matrix. Within this matrix the different alternatives (feedstocks) will be assessed against the established criteria. In this study four of the most commonly researched alternatives to petrochemicals for bio-based chemical feedstocks were studied: A1: Algae Biomass, A2: Lignocellulosic Biomass, A3: Agricultural Residues, A4: Vegetable Oils. Five key evaluation criteria (C1–C5) have been identified, based upon a comprehensive review of existing research and expertise in the field. These criteria capture all of the supply side, economic, environmental, and market-related factors that are relevant to the production of bio-based chemicals.

- **C1: Availability**: The extent to which a feedstock can consistently provide sufficient quantity of feedstock to meet production demands and be available across a wide geographic area. A feedstock with high availability ensures that there is no interruption to production and provides less risk to the supply chain.
- **C2: Cost ($/ton)**: This criterion assesses the cost of acquiring and processing each of the feedstocks. Generally speaking, lower costs provide an advantage to the economics of a project; however, within the context of the normalized decision matrix, higher scores reflect better cost performance than lower scores.
- **C3: Conversion Efficiency**: The conversion efficiency of a feedstock reflects how effectively a given amount of biomass is converted to the desired product(s) through either biochemical or thermochemical routes. Improved conversion efficiencies lead to increased process yields and improved energy utilization.
- **C4: Environmental Impact (Life Cycle Assessment – LCA)**: This criterion assesses the environmental sustainability of the feedstocks based on the environmental impacts associated with the life cycle of the feedstocks including but limited to greenhouse gas emissions, energy consumption, land use requirements, and water usage. A feedstock with fewer environmental impacts receives a higher score.
- **C5: Market Demand**: This criterion assesses the current and future demand for the chemical products that are produced from the feedstocks. The degree of commercialization and long-term economic sustainability of a feedstock is largely dependent on the level of demand for these products. Qualitative and/or quantitative assessments from various literature sources are then used to convert the assessments into a normalized numerical scale (1-5) where a score of "5" indicates the best possible performance while a score of "1" indicates the poorest possible performance.

**Table 1** Qualitative and/or quantitative assessments from various literature

| **Criteria (C)** | **Algae Biomass** | **Lignocellulosic Biomass** | **Agricultural Residues** | **Vegetable Oils** | **Ref.** |
|---|---|---|---|---|---|
| C1: Availability | 4 | 3 | 5 | 4 | [16] |
| C2: Cost ($/ton) | 3 | 4 | 5 | 3 | [17] |
| C3: Conversion Efficiency | 5 | 3 | 3 | 4 | [18] |
| C4: Environmental Impact | 5 | 4 | 4 | 3 | [19] |
| C5: Market Demand | 3 | 4 | 3 | 5 | [17] |

### 3.1. Analytic Hierarchy Process (AHP)

The process for applying AHP can be broken down into the following steps:

- Step 1: Determine the Criteria: - Five common criteria used in selecting a suitable bio-based feedstock were identified through literature review.
- Step 2: Construct Pairwise Comparison Matrix and Normalize Matrix: - Saaty's 1-9 scale was used to construct the pairwise comparison matrix A as shown below. Divide each element by its respective column sum.

**Table 2** Pairwise Comparison Matrix

| Criteria | C1 | C2 | C3 | C4 | C5 | Column Sum |
|---|---|---|---|---|---|---|
| C1 Availability | 1 | 2 | 1/3 | 1/2 | 1 | 7.5 |
| C2 Cost | 1/2 | 1 | 1/3 | 1/2 | 1 | 9 |
| C3 Conversion Efficiency | 3 | 3 | 1 | 2 | 2 | 2.67 |
| C4 Environmental Impact | 2 | 2 | 1/2 | 1 | 2 | 4.5 |
| C5 Market Demand | 1 | 1 | 1/2 | 1/2 | 1 | 7 |

**Table 3** Normalized Matrix

| Criteria | C1 | C2 | C3 | C4 | C5 |
|---|---|---|---|---|---|
| C1 | 0.133 | 0.222 | 0.125 | 0.111 | 0.143 |
| C2 | 0.067 | 0.111 | 0.125 | 0.111 | 0.143 |
| C3 | 0.400 | 0.333 | 0.375 | 0.444 | 0.286 |
| C4 | 0.267 | 0.222 | 0.188 | 0.222 | 0.286 |
| C5 | 0.133 | 0.111 | 0.188 | 0.111 | 0.143 |

The **average of each row** gives the criteria weights.

**Table 4** Compute Priority Weights

| Criterion | Weight |
|---|---|
| C1 Availability | 0.147 |
| C2 Cost | 0.111 |
| C3 Conversion Efficiency | 0.368 |
| C4 Environmental Impact | 0.237 |
| C5 Market Demand | 0.137 |

Highest importance is assigned to Conversion Efficiency, followed by Environmental Impact, which aligns well with sustainability-driven feedstock selection.

**Step 4: Consistency Check**

$\lambda_{max} \approx$ **5.21**

**Consistency Index (CI)** = $(\lambda_{max} - n)/(n - 1) = (5.21 - 5)/4 =$ **0.0525**

**Random Index (RI)** for n = 5 → **1.12**

Consistency Ratio (CR)

CR=CI / RI=0.0525 / 1.12=0.0469

**CR < 0.10 → Judgements are consistent**

**Table 5** Final AHP Weights

| Criterion | Final Weight |
|---|---|
| Availability | 0.15 |
| Cost | 0.11 |
| Conversion Efficiency | 0.37 |
| Environmental Impact | 0.24 |
| Market Demand | 0.13 |

The relative weight of each selection criterion was determined using the Analytic Hierarchy Process (AHP). The AHP weights indicate that both conversion efficiency (0.37) and environmental impact (0.24) have the highest weights and therefore are the most influential factors for feedstock selection. Availability (0.15), market demand (0.13) and cost (0.11) follow. Consistency Ratio (CR = 0.047) indicates that the judgements are consistent.

### 3.2. TOPSIS/VIKOR using AHP weights

**Table 6** Criteria & AHP Weights

| Code | Criterion | Type | Weight ($w_j$) |
|---|---|---|---|
| C1 | Availability | Benefit | 0.15 |
| C2 | Cost | **Cost** | 0.11 |
| C3 | Conversion efficiency | Benefit | 0.37 |
| C4 | Environmental impact | Benefit | 0.24 |
| C5 | Market demand | Benefit | 0.13 |

**Table 7** Decision Matrix (Scores: 1–5)

| Alternative | C1 | C2 | C3 | C4 | C5 |
|---|---|---|---|---|---|
| A1 Algae | 4 | 3 | 5 | 5 | 3 |
| A2 Lignocellulosic | 3 | 4 | 3 | 4 | 4 |
| A3 Agri-residues | 5 | 5 | 3 | 4 | 3 |
| A4 Vegetable oils | 4 | 3 | 4 | 3 | 5 |

#### *3.2.1. PART A: TOPSIS Method*

Step 1: Normalized Decision Matrix (R)

$$r_{ij} = \frac{x_{ij}}{\sqrt{\sum x_{ij}^2}}$$

**Table 8 N**ormalized Decision Matrix From TOPSIS

| Alt | C1 | C2 | C3 | C4 | C5 |
|---|---|---|---|---|---|
| A1 | 0.49 | 0.38 | 0.67 | 0.62 | 0.39 |
| A2 | 0.37 | 0.51 | 0.40 | 0.49 | 0.52 |
| A3 | 0.61 | 0.64 | 0.40 | 0.49 | 0.39 |
| A4 | 0.49 | 0.38 | 0.54 | 0.37 | 0.65 |

Step 2: Weighted Normalized Matrix (V)

$\boldsymbol{v_{ij}} = \boldsymbol{w_j} * \boldsymbol{r_{ij}}$

**Table 9** Weighted Normalized Matrix

| **Alt** | **C1** | **C2** | **C3** | **C4** | **C5** |
|---|---|---|---|---|---|
| A1 | 0.074 | 0.042 | 0.248 | 0.149 | 0.051 |
| A2 | 0.056 | 0.056 | 0.148 | 0.118 | 0.068 |
| A3 | 0.092 | 0.070 | 0.148 | 0.118 | 0.051 |
| A4 | 0.074 | 0.042 | 0.200 | 0.089 | 0.085 |

**Table 10** Ideal Solutions

| **Positive Ideal ($A^+$)** | | | | | Negative Ideal ($A^-$) | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Max (benefit), Min (cost) | | | | | | | | | |
| C1 | C2 | C3 | C4 | C5 | C1 | C2 | C3 | C4 | C5 |
| 0.092 | 0.042 | 0.248 | 0.149 | 0.085 | 0.056 | 0.070 | 0.148 | 0.089 | 0.051 |

Step 3: Separation Measures & Closeness Coefficient

**Table 11** TOPSIS Ranking

| **Alt** | **$S^+$** | **$S^-$** | **CC** | **TOPSIS Ranking** |
|---|---|---|---|---|
| A1 | 0.038 | 0.121 | **0.761** | **1** |
| A2 | 0.118 | 0.043 | 0.267 | 4 |
| A3 | 0.073 | 0.057 | 0.438 | 3 |
| A4 | 0.072 | 0.085 | 0.541 | 2 |

*3.2.2. PART B: VIKOR Method*

**Table 12** Best ($f^*$) and Worst ($f^-$)

| **Criterion** | **$f^*$** | **$f^-$** |
|---|---|---|
| C1 | 5 | 3 |
| C2 (cost) | 3 | 5 |
| C3 | 5 | 3 |
| C4 | 5 | 3 |
| C5 | 5 | 3 |

Step 1: Compute $S_i$ and $R_i$

$\mathbf{S_i = \sum w_j * (f^* - f_{ij} / f^* - f^-)}$ and $\mathbf{R_i = \max [w_j * (f^* - f_{ij} / f^* - f^-)]}$

| Alt | $S_i$ | $R_i$ |
|---|---|---|
| A1 | 0.130 | 0.065 |
| A2 | 0.563 | 0.185 |
| A3 | 0.445 | 0.185 |
| A4 | 0.258 | 0.120 |

Step 2: Compute $Q_i$ (v = 0.5)

$$Q_i = 0.5\ (S_i - S^* / S^- - S^*) + 0.5\ (R_i - R^* / R^- - R^*)$$

**Table 13** VIKOR Ranking

| Alt | $Q_i$ | VIKOR Ranking |
|---|---|---|
| A1 | 0.000 | 1 |
| A4 | 0.316 | 2 |
| A3 | 0.648 | 3 |
| A2 | 1.000 | 4 |

The combined AHP – TOPSIS and AHP – VIKOR ranking processes identified algae as the best bio based chemical feedstock, because it has a higher conversion efficiency than other options, and provides better environmental characteristics than competing feedstocks. In addition, the consistent rankings provided by each method are an additional validation of the reliability and consistency of the multi-criteria decision-making process presented in this paper.

### 3.3. Sensitivity Analysis of Criteria Weights (±20%)

Sensitivity analyses were performed with respect to AHP Criterion Weights by varying each AHP Criterion Weight by ±20% while proportionately normalizing the other weights to evaluate how sensitive the AHP-TOPSIS and AHP-VIKOR results would be to variations in the weights assigned to individual AHP Criteria. The base case ranking generated from the TOPSIS evaluation was A1 > A4 > A3 > A2.

However, slight improvement in the relative rankings of A3 (agricultural residues) were realized when availability (C1) and cost (C2) criteria were varied; nevertheless, algae biomass (A1) was always the top- or second-ranked option regardless of the variation in the weights assigned to the various criteria. The conversion efficiency (C3) criterion was identified as the most significant factor that affected the final ranking of the options; specifically, a positive variation in this criterion caused algae biomass to become the most preferable option. Also, an increase in the weight given to environmental impact (C4) clearly made algae biomass the preferred option. Conversely, an increase in the weight given to market demand (C5) resulted in vegetable oil (A4) becoming the preferred option; however, algae biomass remained competitive against vegetable oil throughout the sensitivity analysis. Vegetable oils (A4) were the dominant option in only two of the ten scenarios evaluated using VIKOR; these scenarios were the market driven scenario and the extreme cost emphasis scenario. Agricultural residues (A3) became the preferred option in one of the extreme cost emphasis scenarios. All of the VIKOR compromise solutions met both the acceptable advantage condition and the acceptable stability condition for all of the scenarios evaluated. In addition, the overall robustness index values indicated that algae biomass (≥80%) had very high rank stability, vegetable oil had moderate rank stability, and agricultural residues and lignocellulosic biomass had low rank stability.

## 4. Conclusion

The fact that all three methods (TOPSIS, VIKOR, and sensitivity) produced identical or consistent conclusions on the sustainability and effectiveness of algae as a sustainable biomass source for biobased chemicals is evidence that the multi-criteria decision-making approach presented here is reliable and effective.

## Compliance with ethical standards

*Disclosure of Conflict of Interest*

Author do not have any conflict of interest

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